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Interactive comment on "Impacts of Antarctic runoff changes on the Southern Ocean sea ice in an eddy-permitting sea ice-ocean model" *by* V. Haid et al.

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REFEREE #2:

This paper examines the model response of sea ice to the supply of additional freshwater at the surface of the ocean around Antarctica. The model used is NEMO, forced by global atmospheric reanalysis data with LIM2 sea ice model. Five scenarios are examined and compared with a control run. The scenarios include cases where the fresh water "runoff" is distributed uniformly around the coast of Antarctica, and others with regional maxima that approximately coincide with major ice shelves. In a third category the runoff is applied offshore, to mimic iceberg drift. The total magnitude of the runoff also differs between most of the simulations. The authors conclude that fresh water

input increases sea ice extent and volume, up to a "turning point" value whereupon the sea ice trend is inverted. They also find that their experiments are sensitive to the distribution of fresh water runoff at the ocean surface. The paper is well written and readable and makes a useful contribution. One of the more interesting aspects of this paper is that the authors segregate the response of the sea ice into a thermodynamic and a dynamic components. I congratulate the authors on this part of their discussion.

MAIN COMMENTS

1. This is a topic of current interest, as evidenced by the fact that at least two highly relevant papers have appeared in the literature in the time that this article has been in process. Some details of the present paper need to acknowledge the publication of these two studies. They are Merino, N. J. Le Sommer, G. Durand, N. Jourdain, G. Madec, P. Matthiot and J. Tournadre, (2016) Antarctic icebergs melt over the Southern Ocean: climatology and impact on sea-ice. Ocean Modelling, 104, 99-110, doi:10.1016/j.ocemod.2016.05.001 Pauling, A.G., C. M. Bitz, I. J. Smith, and P. J. Langhorne, (2016) The response of the Southern Ocean and Antarctic sea ice to fresh water from ice shelves in an Earth System Model. J. Climate, 29, 1655–1672. doi: http://dx.doi.org/10.1175/JCLI-D-15- 0501.1

AUTHORS:

We thank the referee for suggesting these new publications. We added the mentioned articles to the list of previous studies. Section 1. includes now the following text: "Merino et al. (2016) used an iceberg model coupled to a sea ice-ocean model to establish a seasonal climatology of iceberg melt for the Southern Ocean and find that the iceberg melt water leads to higher sea ice concentration and thickness, with exception of the Amundsen/Bellingshausen Sea area. Pauling et al. (2016) employed an Earth-system model to investigate the Southern Ocean sea ice response to artificially augmented freshwater input. They tested the sensibility to higher freshwater additions than current estimates and previous studies and compare an iceberg model-based surface distribution with a coastal distribution at depth. They conclude that the effect of the different distributions on the mixed layer depth is contrary but the sea ice response is similar in both cases."

REFEREE #2:

2. An interesting aspect is the hypothesis that a large amount of freshwater will reduce the sea ice. I am not sure I understand why this is the case. In addition, as the conclusion is based on one experiment, and as I could not see a clear pattern in the qualitative behaviour of the system with increasing freshwater flux, my opinion is that the authors need to work a little harder to be convincing.

AUTHORS:

We agree with the referee that the "turning point" conclusion based on only one experiment might be not solid enough. Therefore, we refrain from any statements presenting turning point as a fact. However, we find the results from that experiment very interesting and contrary to our expectations. This prompts us to show our findings and suggest a possible interpretation of them with the due caution. As to the question why there may be a turning point, we offer a possible explanation at the end of Section 3.2 p.10, which we have adapted after reconsidering the involved processes: "During autumn the sea ice production of S5 surpasses that of S2, since the lower surface salinity facilitates ice formation. However, during winter and spring S2 features higher ice production values, because the influence of the offshore areas, particularly the northeastern Weddell and Ross Seas, becomes dominant. As a possible underlying mechanism, we suggest that the increased velocity is not limited to the coastal current but spreads to the subpolar gyres. A stronger circulation in a cyclonic gyre causes increased upwelling in the gyre's center due to the increased Ekman transport at the surface. In the Weddell and Ross Seas, this would cause a local increase of surface temperatures and salinities (SSS). In S5, SST and especially SSS in the winter mean is higher than in S2 in the northeastern Weddell Sea and northeastern Ross Sea (figures of the SST and SSS

difference between experiments S2 and S5 are provided as Supplement S2). In consequence ice production is reduced and ice melt furthered. A reduced sea ice cover, especially in the regions close to the winter ice edge, leads to a higher heat uptake from solar radiation during the summer, triggering a positive feedback loop (Stammerjohn et al., 2012). Additionaly, there is a second way, the increased speed of the coastal ice drift can contribute to the difference in sea ice volume and extent between S2 and S5: it shortens the period of time available for thermal growth and it can strengthen the mechanical processes thickening the ice in areas of convergence. Depending on the regional geometry and the ice drift pattern, either the thermodynamic or the dynamic effect on the sea ice thickness prevails and leads to thinner or thicker sea ice, respectively. While in WRoS, the sea ice in S5 is thicker than in S2 due to compression against the shoreline, the thermodynamic effect is of greater influence in WWeS, where large areas feature thinner ice in S5 (Figure 2h and q)." And summarize again in the Conclusions (Section 5):"Based on this we think it probable that a turning point in the sea ice response to freshwater forcing exists and offer the following mechanism as a possible explanation: The coastal freshwater input changes the SSH slope and increases not only the velocities in the coastal current, but also of the subpolar gyres. Due to the increased Ekman transport more warm and saline water wells up in the gyres' centres., SST (and SSS) will increase and lead to enhanced melting of the northward advected sea ice and reduced local ice production during autumn and winter. The reduced sea ice cover allows higher shortwave radiation absorption by the ocean and triggers a positive feedback loop. Also, the freshwater-induced acceleration of the coastal current leads to thinner sea ice, when the time available for thermodynamical growth is reduced strongly. This is especially relevant for the Weddell Sea, while in the western Ross Sea all performed experiments result in dynamically thickened sea ice."

REFEREE #2:

3. In relation to this, please can you explain why the simulations of sea ice are considered to represent sea ice behaviour, while the simulation period of 10 years is too

short for the water characteristics to reach equilibrium (see e.g. p. 2, line 28-33). Are you saying that you are investigating sea ice response processes and therefore do not need to reach equilibrium? If this is the case, I am not sure I understand how you may conclude that there is a reversal of behaviour when more than a certain amount of fresh water (undetermined from these experiments) is added to the system. How can you tell that this is not due to variability between runs? This may require more explanation of the known behaviour of the model. The existence of a turning point based on evidence of a single simulation requires additional argument for its existence.

AUTHORS:

The response times of ocean surface and deeper layers of the ocean to changes from the surface differ strongly. We are confident that the surface and the sea ice reaches near-equilibrium state within a fraction of the simulation period. We consider especially the differences between experiments to be reliable and due to the differences in runoff input since they present the only source of variability between the runs. For these two reasons, we think the results trustworthy, although the ocean at depth is not in an equilibrium state. With the complexity of today's ocean models and the short run period of our experiments it is possible that the difference we see between experiments S2 and S5 does not proof a turning point, however to the authors of this article the proposed explanation seems the most probable. The suggestion is not based on the result of one experiment, but on the difference we observe between two experiments. However, we agree with the referee that before stating the existence of this turning point as a fact further investigation is needed. We slightly altered the wording to enhance the speculative character of our suggestions.

REFEREE #2:

4. How was the seasonal variation in ice shelf "runoff" decided (see Fig 1e)?

AUTHORS:

There is not much known about the seasonality of Antarctic runoff. However seasonality can be expected for both, iceberg meltwater and basal melting. In the first case the seasonality is strong (e.g. Merino et al., 2016) since the ocean surface heats up in summer. In the latter case uncertainties are large, but in winter the dense water formation in coastal polynyas inhibits warm water intrusions under the ice shelves and therefore a higher heat flux into the cavities can be expected during the summer. The runoff in our reference run is obtained from the DRAKKAR group (Bourdalle-Badie and Treguier 2006), who adapted the figures given by Dai and Trenberth (2002) and Jacobs et al. (1992) for the ORCA025 grid.

REFEREE #2:

5. Development in time and variability on p. 9: How much is know about variability between model runs when there has not been a repeat of an experiment? Perhaps this is well known for the model and could be briefly explained to the reader.

AUTHORS:

The model variability is low and a repeat of any experiment is expected to give the same results, since the runtime of only ten years does not give the small numerical errors the time to grow into variability of any significance.

REFEREE #2:

6. Comments 2-5 lead me to be unconvinced by the authors' conclusion that (the small) freshwater input they apply causes the sea ice to expand, while a larger input inverts the trend. This needs to be very carefully re-evaluated.

AUTHORS:

We agree that the presented experiments do not proof the existence of a turning point in the sea ice response. However, we are of the opinion that they strongly suggest such a behaviour. The differences in output between our experiment S2 and S5 are not random, but the result of the differences in the model input. We checked our wording to avoid misrepresentation of the turning point as a hard fact.

REFEREE #2:

TECHNICAL COMMENTS

p. 2, line 9-10: Merino et al and Pauling et al (2016) need to be added to the previous studies.

AUTHORS:

We added Merino et al. (2016) and Pauling et al. (2016) to the previous studies. We added the following text in Section 1: “Merino et al. (2016) used an iceberg model coupled to a sea ice-ocean model to establish a seasonal climatology of iceberg melt for the Southern Ocean and find that the iceberg melt water leads to higher sea ice concentration and thickness, with exception of the Amundsen/Bellingshausen Sea area. Pauling et al. (2016) employed an Earth-system model to investigate the Southern Ocean sea ice response to artificially augmented, constant freshwater input. They tested the sensibility to higher freshwater additions than current estimates and previous studies and compare an iceberg model-based surface distribution with a coastal distribution at depth. They conclude that the effect of the different distributions on the mixed layer depth is contrary but the sea ice response is similar in both cases.” We added the following passages to section 3.3: “ increase in Antarctic runoff leads to an increase in sea ice in accordance with e.g. Bintanja et al. (2013), Bintanja et al. (2015) and Pauling et al. (2016).” “While Pauling et al. (2016) with even higher amounts of fresh water addition did not conclude the existence of a turning point, their experiment with the highest amount of fresh water yields the lowest seasonal linear trends for the sea ice, while the lowest fresh water amount in summer and winter yields the least negative and in autumn even a positive trend (their Figure 11). ” “In particular, as also Merino et al. (2016) found, considering an idealized freshwater discharge from icebergs strongly impacts sea ice thickness” “Pauling et al. (2016) recently found the depth distribution of additional fresh water in the Southern Ocean to be of small effect

on the sea ice.”

REFEREE #2:

p. 2, line 24-25: Note that Pauling et al (2016) have added fresh water spatially distributed according to ice shelves, and at the depth of the ice shelf. However their simulations did not vary in magnitude through the year.

AUTHORS:

Mentioned in the newly added text (see answer above).

REFEREE #2:

p. 2, line 28-33: (as main comment) Please can you explain why the simulations of sea ice are considered to represent sea ice behaviour, while the simulation period of 10 years is too short for the water characteristics to reach equilibrium. Are you saying that you are investigating sea ice response processes and therefore do not need to reach equilibrium? If this is the case, I am not sure I understand how you may conclude that there is a reversal of behaviour when more than a certain amount of fresh water (undetermined from these experiments) is added to the system. How can you tell that this is not due to variability between runs? This may require more explanation of the known behaviour of the model. The existence of a turning point based on evidence of a single simulation requires additional argument for its existence.

AUTHORS:

Answered above (Main comments #2 and #3)

REFEREE #2:

p. 4, line 5-6: Was Dai and Trenberth (2002) applied in all other parts of the globe, apart from Antarctica? Was the seasonal variation used (see Fig 1a – actually I think it is 1e) from Dai and Trenberth (2002)? If so how do you justify using the seasonal behaviour for river runoff to represent melting ice shelves?

AUTHORS:

The runoff data in the reference run is obtained from the DRAKKAR group (Bourdalle-Badie and Treguier, 2006) and is based on Dai and Trenberth (2002) for all the globe except Antarctica, where it relies on Jacobs et. al. (1992). The seasonal cycle of the Antarctic runoff was introduced by the DRAKKAR group. To more clearly explain this, we changed the description in the article to: “The river run-off data is a monthly climatology based on the studies of Dai and Trenberth (2002) and Jacobs et al. (1992) and adapted for the ORCA025 grid by the DRAKKAR group (Bourdalle-Badie and Treguier, 2006).” and added the references. The melt of the Antarctic glacial ice in the Southern ocean is primarily dependent on the water temperature. For the basal melt of the ice shelves the main question is therefore how much warm water can intrude onto the continental shelves. In winter, deep convection linked to polynya activity hinders the warm water intrusions and thus higher melt rates can be expected in the summer months. Also for iceberg melt the seasonal dependence is strong due to the surface warming (Merino et al., 2016). We admit that there is limited knowledge of the seasonal cycle of the Antarctic ’runoff’. The runoff in our study therefore may not be correct in amplitude or shape, but some seasonal variation of the meltwater may be expected.

REFEREE #2:

p. 4: Table 1 is very useful but has not been referred to in the text. It would be useful to refer to it in section 2.2.

AUTHORS:

A reference was added in the text p.4, l. 16. “A short overview over the experiments and their differences is also given in Table 1.”

REFEREE #2:

p. 4, lines 12-33: I think that the subfigures of Fig. 1 have been mislabeled.

AUTHORS:

Yes, we apologize for the mix-up. The mistake is now corrected.

REFEREE #2:

p. 4-5: Experiment design – please note that Merino et al (2016) and Pauling et al (2016) both conduct experiments with fresh water distributed to mimic iceberg melt.

AUTHORS:

In this section, we describe only our own experiments. However, both mentioned studies are now added with mention of the iceberg model-derived distribution in the introduction chapter.

REFEREE #2:

p. 5, line 20 onwards: This is a very interesting discussion regarding the influence of additional fresh water at the surface on the SSH, the velocity and thus on sea ice thickness. I was confused about how changes in the direction of the velocity were taken into account? Does the right hand column of Fig 2 show speed not velocity?

AUTHORS:

The right hand column of Figure 2 shows the velocity differences as arrows underlaid by the difference in speed following the colour scale.

REFEREE #2:

p. 5: Spatial Response Patterns: How can you have a high confidence interval in the difference when, at each time step, there are only two quantities? Is it time-averaged?

AUTHORS:

The confidence level was determined using the Student’s t-test for dependent data samples. The ’sampling period’ was limited to the 10*6 monthly means April-September 2004-2013.

REFEREE #2:

Fig 2 is for the “winter” months. Which months are “winter”?

AUTHORS:

We do refer to ’winter’ as the 6-month period from April to September as mentioned p. 5, l. 14. A short statement was added there to improve clarity. “In the following, the word winter referring to a specific time period will mean the months April-September.”

REFEREE #2:

p. 6: line 9-10: Is a salinity-dependent freezing point coded in the model?

AUTHORS:

Yes, in the LIM2 sea ice model, the freezing temperature of seawater depends on salinity, linearly with an empirical constant.

REFEREE #2:

p. 6, line 23 + p.7, lines 14, 27, 28, + p. 8, line 12, + p. 13 line 23: use of the word “acceleration” when I think you mean “faster speed”

AUTHORS:

Yes, not in all cases the words accelerated/acceleration were used in their proper sense. We corrected the phrasing where necessary.

REFEREE #2:

p. 7, line 26: please mark Princess Martha Coast on a map.

AUTHORS:

Princess Martha Coast was marked on the map in Fig. 1b)

REFEREE #2:

p. 8, line 10: please mark Filchner/Ronne Ice Shelf on a map

AUTHORS:

We consider the Filchner/Ronne Ice Shelf to be a well known feature of the Antarctic geography like e.g. the Ross Ice Shelf, Amundsen Sea and Antarctic Peninsula. We are afraid readers unfamiliar with the main features of the Antarctic geometry will have to refer to a map from another source.

REFEREE #2:

p. 9, line 10-12: Why are the larger amplitude anomalies in 2009-2011? Why are the anomalies smaller in 2012-2013?

AUTHORS:

We cannot answer this question completely. As mentioned in the article, regional time series show that the difference occurs in the Amundsen, Bellingshausen and western Weddell Seas. We therefore assume that the atmospheric circulation features a regional shift in those years that has a much stronger effect on the experiments with regionally varied runoff than on the experiments with uniform coastal runoff.

REFEREE #2:

p. 10, line 9-15: We are not shown the surface salinity or the SST so it is difficult to follow this discussion. Could the essential elements be presented in a figure?

AUTHORS:

Figures of the difference in SSS and SST between runs S2 and S5 are added as Supplements S2. In the article that fact is now mentioned: ”(figures of the SST and SSS difference between experiments S2 and S5 are provided as Supplement S2)”.

REFEREE #2:

p. 11, line 13 & line 16: I believe it is more appropriate to state as estimates 6 – 24% and 5 – 23% .

AUTHORS:

We agree and rounded the given percentages.

REFEREE #2:

p. 13, line 23: Stammerjohn et al (2012) have shown that there is strong correspondence between anomalies in the timings of sea ice retreat and subsequent advance, and you may wish to refer to this paper. Stammerjohn, S., R. Massom, D. Rind, and D. Martinson (2012), Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, Geophys. Res. Lett., 39, L06501, doi:10.1029/2012GL050874.

AUTHORS:

We thank the referee for the suggestion. The reference was added in the article: "A reduced sea ice cover, especially in the regions close to the winter ice edge, leads to a higher heat uptake from solar radiation during the summer, triggering a positive feedback loop (Stammerjohn et al., 2012). "

REFEREE #2:

p. 13, line 23: Why would there be sea ice melt in winter? Is there evidence for this in the model runs?

AUTHORS:

If the SST is above the freezing point, sea ice melts. In the weakly stratified Southern Ocean heat can be transported to the surface with relative ease. In the Weddell Sea this has lead to the occurrence of the well-known Weddell polynya in the 1970s. Here, ice is advected northward into regions that still retain heat from the summer months. To improve understanding, the wording was changed. "If the stratification of the offshore water column is increased, SST will increase during summer and lead to enhanced melting of the northward advected sea ice and reduced local ice production."

REFEREE #2:

p. 14, line 2: replace "lose density" with "density reduces"

AUTHORS:

The wording has been changed. "the dense shelf waters become warmer, fresher and hence less dense."

REFEREE #2:

p. 14, line 12-13: Some experiments have been done by Pauling et al (2016).

AUTHORS:

The study by Pauling et al. 2016 has been added in the Introduction chapter and the section 3.3.

REFEREE #2:

Fig 1: I did not understand the caption at all. I also think that the sub-figures are mislabeled. Please give a key for regions 1-10 in a).

AUTHORS:

Yes, the subplots were mislabelled. The mistake was corrected. A key for the regions was added in the figure caption.

REFEREE #2:

Fig 2: Do you mean speed rather than velocity? What months are represented? How is the t-test performed when it is the difference between only 2 quantities?

AUTHORS:

In the right hand column the colour scale refers to speed, while the arrows depict velocity. A short explanatory text was added to the caption. "The colors underlaying the velocity arrows indicate speed." The 'winter' period in our article always refers to the months April-September. The t-test for dependent samples is performed on the time series of the two quantities. The 'sampling period' was limited to the 10*6 monthly means April-September 2004-2013.

REFEREE #2:

Fig 3 b, d, f.: Are the large jumps in values between month 1 and month 12 expected?

AUTHORS:

They correspond to what is also visible in the time series in a), c), e) and are not beyond what is expected. The seasonal cycle of the runoff addition may play a role here and cause a stronger seasonal signal in the sea ice properties.

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